

A Search for the Fourth SM Family: Tevatron still has a Chance

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Abstract

Existence of the fourth family follows from the basics of the Standard Model and the actual mass spectrum of the third family fermions. We discuss possible manifestations of the fourth SM family at existing and future colliders. The LHC and Tevatron potentials to discover the fourth SM family have been compared. The scenario with dominance of the anomalous decay modes of the fourth family quarks has been considered in details.

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I. INTRODUCTION

Even though the Standard Model with three fermion families (SM3) accounts for almost all of the large amount of the particle physics phenomena [1], there are a number of fundamental problems which cannot be addressed in the framework of the SM3: quark-lepton symmetry, fermion's mass and mixing pattern, family replication and the number of families, L-R symmetry breaking, electroweak scale etc. In addition, SM3 contains unacceptably large number of arbitrary free parameters put by hand: 19 if the neutrinos are massless, 26 if neutrinos are Dirac particles and more than 30 if neutrinos are Majorana particles. Flavor Democracy Hypothesis (FDH), which is quite natural in respect to the SM basics, provides a partial solutions to the above-mentioned problems, namely: sheds light on fermion's mass and mixing pattern, implies the number of SM families to be 4 and reduces the number of free parameters [2–4] (see also reviews [5–10] and references therein).

Historical analogy: Let us emphasize the analogy of today's SM fermions and parameters inflation with chemical elements inflation in 19th century and hadron inflation in 1950–1960. The both cases have been clarified through four stages: systematics, predictions confirmed, clarifying experiments, new basic physics level (see Table I). We have added the last row to the Table in order to reflect present situation in particle physics.

Let us remind that flavour physics met a lot of surprises. The first example was discovery of μ -meson (We were looking for π -meson predicted by Yukawa but discovered the “heavy electron”). The next example was represented by strange particles (later we understood that they contains strange quarks). The story was followed by τ -lepton, c- and b-quarks discovered in 1970's. Actually, c-quark was foreseen by GIM mechanism and quark-lepton symmetry and its mass was estimated in the few GeV region, whereas the discovery of τ -lepton and b-quark was completely surprising for physicists. According to the Standard Model they are the members of the third fermion family, which was completed by the discovery of t-quark in 1995 at Tevatron. Actually, we need at least three fermion families in order to handle CP-violation within the SM [11]. CP violation is necessary for the explanation of Barion Asymmetry of the Universe (BAU). Unfortunately, SM with three fermion families does not provide actual magnitude for BAU. Fortunately, the fourth SM family could provide additional factor of order of 10^{10} and, therefore, solves the problem [12].

Inflation	Systematic	Confirmed Predictions	Clarifying experiments	Fundamentals
Chemical Elements	Mendeleyev Periodic Table	New elements	Rutherford	p, n, e
Hadrons	Eight-fold Way	New hadrons	SLAC DIS	quarks
SM fermions	Flavor Democracy	Fourth family ?	LHC ?	Preons ?

Table I: Historical analogy

The status of the fourth SM family (SM4) was clearly emphasized at dedicated international workshop held at CERN in September 2008. The outcome of the workshop was published in a paper titled “Four statements about the fourth generation” [13]. These statements are:

1. The fourth generation is not excluded by EW precision data.
2. SM4 address some of the currently open questions.
3. SM4 can accommodate emerging possible hints of new physics.
4. LHC has the potential to discover or fully exclude SM4.

In our opinion the last statement is the most important one, because, indirect manifestations could have many different explanations, the existence of the fourth SM family will be proved with the direct discovery of its quarks and leptons. Current experimental bounds on the masses of the fourth SM family fermions are as follows [1]:

$$\begin{aligned}
m_{u_4} &> 256 \text{ GeV}, \\
m_{d_4} &> 128 \text{ GeV (100\% CC decays); } m_{d_4} > 199 \text{ GeV (100\% NC decays)}, \\
m_{l_4} &> 100.8 \text{ GeV}, \\
m_{\nu_4} &> 90.3 \text{ GeV (Dirac type), } m_{\nu_4}(\textit{light}) > 80.5 \text{ GeV (Majorona type)}.
\end{aligned}$$

By this time almost all papers on the SM4 searches consider only SM decay modes. However, it is possible that anomalous decay modes could be dominant, if some criteria is met [14]. In this case, the search strategy should be changed drastically and current low limits from Tevatron experiments are not valid.

The scope of the paper is following: in Section 2 we give a brief review of the Flavor Democracy Hypothesis and discuss possible manifestations of the fourth SM family at existing and future colliders. Then, we concentrate on the scenario with dominance of the anomalous decay modes of the fourth family quarks. The criteria for this dominance are

considered in Section 3. In Section 4 we consider pair production at the Tevatron and LHC with subsequent anomalous decays. Section 5 is devoted to investigation of anomalous resonant production of the fourth family quarks with subsequent anomalous decays. Finally, in Section 6 we present concluding remarks and recommendations.

II. WHY THE FOUR SM FAMILIES ?

First of all, the number of fermion families is not fixed by the SM. But the asymptotic freedom restricts this number from above, namely, $N \leq 8$. Then, the number of SM families with “massless” neutrinos (which means $m_\nu < m_Z/2$) is determined to be equal to 3 by the LEP1 data. Therefore, number of families could be any number between 3 and 8, inclusively. The most of the free parameters (put by hand) in the SM comes from the Yukawa interactions between the SM fermions and the Higgs doublet, which provides fermion masses and mixings through Spontaneous Symmetry Breaking (SSB). It should be noted that before the SSB, fermions with the same quantum numbers are indistinguishable. Naturally, all Yukawa coupling constants for indistinguishable fermions should be the same. This is the first assumption of the Flavor Democracy Hypothesis. If there is only one Higgs doublet all fundamental fermions (up and down type quarks, charged leptons and neutrinos) should have the same Yukawa coupling constants, since all fermions interact with the same Higgs field. This is the second assumption of the FDH. After the SSB these assumptions in the case of N SM families result with $N - 1$ fermion families to be massless and the N 'th family to be heavy and degenerate. By taking into consideration masses of the third SM family, the FDH implies at least the existence of the fourth SM family [2–4]. In this case, the masses of the first three family fermions come from the slight violation of the full democracy [15–17].

There are two arguments against the existence of the fifth SM family [7, 9, 10]. The first one is the large value of the t -quark mass: in the case of 5 SM families the FDH gives $m_t \ll m_4 \ll m_5$, but it contradicts to partial-wave unitarity constraint $m_Q \leq 700 \text{ GeV} \approx 4 m_t$. The second argument is the neutrino counting at the LEP1: data gives three “massless” non-sterile neutrinos, whereas in the case of the five SM families the FDH predicts this number to be four.

The main reason why the HEP community has objected against the fourth SM family so far comes from the incorrect interpretation of the electroweak precision data. This inter-

pretation since 1990's has been included into PDG reports published bi-annually in leading HEP journals. It should be noted that recent opinion [18] of the writers of the corresponding part of PDG reports is not as strict as it was. Actually in a number of papers published during the last decade [19–27] it has been shown that the precision data and the SM4 are not mutually exclusive. It is interesting that the updated precision data is shifted into the direction of SM4 predictions. For the investigation of the compatibility of the precision data with the fourth SM family and other physics beyond the SM3 a new code named OPUCEM [27, 28] has been developed very recently. Using this code we determined the validity of SM4 with a given set of parameters, namely, $m_{u_4} = 410$ GeV, $m_{d_4} = 390$ GeV, $s_{34} = 0.01$ (CKM mixing between fourth and third SM family quarks), $m_{\nu_4}(l) = 105$ GeV for light Majorana neutrino, $m_{l_4} = 450$ GeV, $m_H = 290$ GeV and $m_{\nu_4}(h) = 2300$ GeV for heavy Majorana neutrino. This set is favored by FDH if the common Yukawa coupling for all SM4 fermions is equal to the $SU_W(2)$ gauge constant g_W ($m_H = 290$ GeV corresponds to quartic coupling of Higgs field equal to g_W). Result is $R = 0.97$ which is two times better than SM3 value $R = 1.7$ (here $R = \Delta\chi^2$ denotes the “distance” from the central values of S and T parameters, for details see [27, 28]).

Actually, there is an infinite number of SM4 points (analog of the well known SUGRA points) which are in better agreement with precision EW data than the SM3. In Table II we present three of them. In Figure 1 we present these points in S-T plane together with SM3 predictions. It is seen that SM4 points are closer to central values of S and T parameters.

A. Indirect manifestations

The existence of the fourth SM family could lead to a number of different manifestations [13], such as essential contribution to the baryon asymmetry of the Universe (SM3 case does not provide enough amount of CP violation), explanation for a 2.5σ deviation from SM3 predictions on B-meson decays observed by Tevatron and B-factories etc. It should be noted that these are not a validation, but just an indication of the fourth SM family, since there are a lot of models (including SUSY) which potentially could lead to the same manifestations. However, the essential enhancement (from 9 times at $m_H \approx 150$ GeV to 4 times $m_H \approx 500$ GeV) of Higgs boson production via gluon-gluon fusion at hadron colliders [29–37] could not be provided by other models. This enhancement could give to Tevatron an opportunity to

SM4 points	1	2	3	SM3
m_{u_4} , GeV	410	440	440	-
m_{d_4} , GeV	390	390	390	-
m_{l_4} , GeV	450	390	390	-
$m_{\nu_4}(\text{L})$, GeV	105	91	95	-
$m_{\nu_4}(\text{H})$, GeV	2300	2900	2900	-
m_H , GeV	290	250	115	115
s_{34}	0.01	0.02	0.02	-
R	0.97	0.56	0.036	1.7
S	0.17	0.15	0.09	0
T	0.19	0.16	0.12	0

Table II: S, T and R parameters for there SM4 points and SM3.

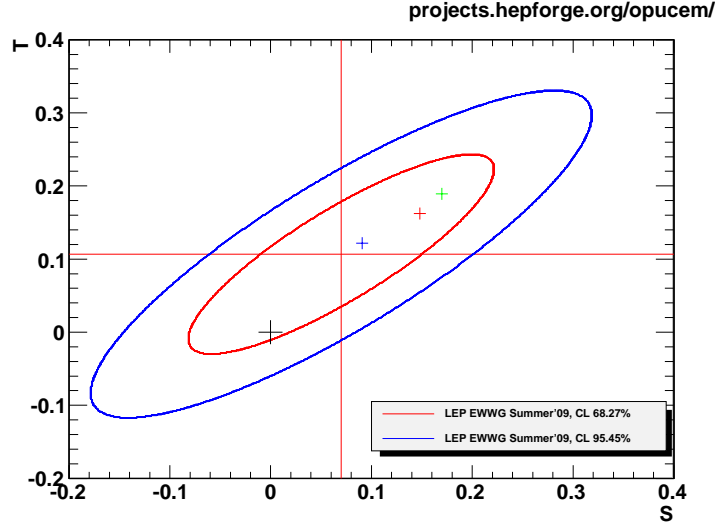


Figure 1: SM3 and three SM4 points in S-T plane. The 1 and 2σ error ellipses represent the 2009 results of the $U = 0$ fit from LEP EWWG. Black crucifix corresponds to SM3 with $m_H = 115$ GeV; green, red and blue crucifixes correspond to SM4 points 1, 2 and 3 from Table 2, respectively.

discover Higgs boson before the LHC [35, 37]. Very recent combined results of CDF (with 4.8 fb^{-1}) and D0 (with 5.4 fb^{-1}) searches for a standard model Higgs boson in the process $gg \rightarrow H \rightarrow W^+W^-$ exclude $131 \text{ GeV} < m_H < 204 \text{ GeV}$ region in the SM4 case [38]. This excluded region will be essentially enlarged with the accumulated luminosity, or Higgs boson

Colliders	Beams	\sqrt{s} , TeV	L , $10^{32} \text{ cm}^{-2} \text{ s}^{-1}$	$L_{int}(2012)$, fb^{-1}
Tevatron	$p\bar{p}$	1.96	3.5	12
LHC 1	pp	7	$0.01 \rightarrow 1$	1
LHC 2	pp	10	10	
LHC 3	pp	14	100	
QCD-E 1	$ep, \gamma p$	1.4	30	
QCD-E 2	$ep, \gamma p$	1.98	10	
Linac-LHC EF	$ep, \gamma p$	3.74	3	
ILC 1	$e^-e^+, \gamma e, \gamma\gamma$	0.5	100	
ILC 2	$e^-e^+, \gamma e, \gamma\gamma$	0.8	100	
CLIC 1	$e^-e^+, \gamma e, \gamma\gamma$	0.5	100	
CLIC 2	$e^-e^+, \gamma e, \gamma\gamma$	1	100	
CLIC 3	$e^-e^+, \gamma e, \gamma\gamma$	3	100	
Muon collider	$\mu\mu$	4	100	

Table III: Parameters of existing and planned TeV scale colliders

will be observed at Tevatron if it has appropriate mass. Moreover, simultaneous discovery of both the Higgs boson and the fourth family neutrino is probable at early stages of LHC operation or at the Tevatron [39–41].

B. Direct manifestations

Obviously, the discovery of the fourth SM family may be only provided by their production and observation at high energy colliders. The fourth family quarks will be copiously produced in pairs at the LHC [5, 30, 44] when the designed center of mass energy and luminosity values is achieved. However, Tevatron still has a chance to observe u_4 before the LHC if u_4 mass is less than 425 GeV (current low limit is 340 GeV from CDF with 4.6 fb^{-1}). If the fourth family quarks mix dominantly with first two families, u_4 and d_4 quarks will give the same signature and observation limit will be extended to 450 GeV.

In Table III we present the center of mass energies and luminosity values of exsisting and planned TeV scale colliders (see [6, 8, 42, 43] and refs therein). Observational possibilities

Colliders	Tevatron	LHC	ILC/CLIC		
Beams	$p\bar{p}$	pp	e^+e^-	γe	$\gamma\gamma$
$q_4(P)$	if KA	VG	if KA, VG	-	if KA
$\bar{u}_4 d_4(AP)$?	?	-	-	-
$q_4(S)$	“large” V_{4i}	“mid” V_{4i}	-	-	-
$q_4(S, A)$	“low” Λ , Res	“mid” Λ , Res	“low” Λ	-	“low” Λ
$l_4(P)$?	?	if KA, VG	-	if KA, G
$\nu_4(P)$?	G	if KA, VG	-	-
$l_4\nu_4(AP)$?	G	-	-	-
$l_4(S, A)$?	?	“low” Λ	“mid” Λ , Res	“low” Λ
$\nu_4(S, A)$?	?	“low” Λ	-	-
Scalar Quarkonia	-	?	-	-	if KA, G
Vector Quarkonia	-	?	if KA, G	-	-
Hadrons	-	?	if KA, G	-	if KA

Table IV: Production of the fourth SM family fermions at existing and planned high energy colliders. Abbreviations are: P (Pair production), AP (Associate Pair production), S (Single production through CKM mixings), A (production through Anomalous interactions), KA (Kinematically Allowed), Res (Resonant production), G (Good), VG (Very Good). V_{4i} denotes corresponding CKM matrix elements, Λ denotes scale of anomalous interactions.

for fourth SM family fermions at these colliders are presented in Tables IV and V. The direct production of the fourth SM family quarks and leptons at TeV scale colliders, namely, Tevatron, LHC, QCD Explorer, Linac-LHC Energy Frontier, ILC, CLIC and muon collider have been considered in a number of papers [45–61, 64–78] (this list includes publications appeared during last decade, see also fourth family web pages [79, 80]). In Tables VI and VII it is given the classification of these papers according to colliders and processes considered.

colliders	Linac-LHC				Muon Collider
	QCD Explorer		Energy Frontier		
Beams	ep	γp	ep	γp	$\mu\mu$
$q_4(P)$	if KA	if KA	G	VG	VG
$q_4(AP)$	-	-	-	-	-
$q_4(S)$	“large” V_{4i}	-	“mid” V_{4i}	-	-
$q_4(S, A)$	“low” Λ	“mid” Λ , Res	“mid” Λ	“mid” Λ , Res	“low” Λ
$l_4(P)$	-	-	-	-	VG
$\nu_4(P)$	-	-	-	-	VG
$l_4\nu_4(AP)$	-	-	-	-	-
$l_4(S, A)$	“low” Λ	-	“mid” Λ	-	“low” Λ
$\nu_4(S, A)$	“low” Λ	-	“mid” Λ	-	“low” Λ
Scalar Quarkonia	-	-	-	-	-
Vector Quarkonia	-	-	-	-	VG
Hadrons	-	-	-	-	VG

Table V: Notations as in Table IV.

III. ANOMALOUS DECAY MODES

The effective Lagrangian for anomalous magnetic type interactions of the fourth family quarks is given as [53, 81, 82]:

$$L = \sum_{q_i} \frac{\kappa_\gamma^{q_i}}{\Lambda} e_q g_e \bar{q}_4 \sigma_{\mu\nu} q_i F^{\mu\nu} + \sum_{q_i} \frac{\kappa_Z^{q_i}}{2\Lambda} g_Z \bar{q}_4 \sigma_{\mu\nu} q_i Z^{\mu\nu} + \sum_{q_i} \frac{\kappa_g^{q_i}}{\Lambda} g_s \bar{q}_4 \sigma_{\mu\nu} T^a q_i G_a^{\mu\nu} + H.c. \quad (1)$$

where $F^{\mu\nu}$, $Z^{\mu\nu}$ and $G^{\mu\nu}$ are the field strength tensors of the gauge bosons, $\sigma_{\mu\nu}$ is the anti-symmetric tensor, T^a are Gell-Mann matrices, e_q is electric charge of quark, g_e , g_Z and g_s are electromagnetic, neutral weak and strong coupling constants, respectively. $g_Z = g_e/\cos\theta_W \sin\theta_W$ where θ_W is the Weinberg angle. κ_γ , κ_Z and κ_g are the strength of anomalous couplings with photon, Z boson and gluon, respectively. Λ is the cutoff scale for new physics. This type of gauge and Lorentz invariant effective Lagrangian have been proposed in the framework of composite models for interactions of excited fermions with ordinary fermions

Colliders	Tevatron	LHC	ILC/CLIC		
Beams	$p\bar{p}$	pp	ee	γe	$\gamma\gamma$
u_4 (P), SM decays	[60, 70]	[30, 44, 58, 59, 64, 65, 67]	[48, 55]		[48, 55]
u_4 (P), Anom decays					
d_4 (P), SM decays	[70]	[30, 59, 64, 65, 67, 78]	[48, 55]		[48, 55]
d_4 (P), Anom decays	[14, 45, 60]				
q_4 (AP)					
q_4 (S)		[66]			
q_4 (S, A), SM decays	[51, 53]	[69, 75]	[52]		
q_4 (S, A), Anom decays	[50, 51, 53, 54]	[62, 63, 69]	[52, 62, 63]		
l_4 (P)			[48, 55]		[48, 55]
ν_4 (P)	[77]	[39, 40, 77]	[48, 55, 56]		
$l_4\nu_4$ (AP)		[73]			
l_4 (S, A)		[68]		[71]	
ν_4 (S, A)					
Scalar Quarkonia		[30, 49]			[48, 55]
Vector Quarkonia			[47, 48, 55]		
Hadrons			[47]		

Table VI: The papers considered production of the fourth SM family fermions at existing and planned high energy colliders.

and gauge bosons [81, 82] . For numerical calculations we implement the Lagrangian (1), as well as fourth family SM Lagrangian into the CalcHEP package [83].

The partial decay widths of u_4 for SM ($u_4 \rightarrow W^+q$ where $q = d, s, b$) and anomalous ($u_4 \rightarrow \gamma q, u_4 \rightarrow Zq, u_4 \rightarrow gq$ where $q = u, c, t$) modes are given below:

$$\Gamma(u_4 \rightarrow W^+q) = \frac{|V_{u_4q}|^2 \alpha_e m_{u_4}^3}{16m_W^2 \sin^2\theta_W} \varsigma_W \sqrt{\varsigma_0} \quad (2)$$

where $\varsigma_W = (1 + x_q^4 + x_q^2 x_W^2 - 2x_q^2 - 2x_W^4 + x_W^2)$, $\varsigma_0 = (1 + x_W^4 + x_q^4 - 2x_W^2 - 2x_q^2 - 2x_W^2 x_q^2)$, $x_q = (m_q/m_{u_4})$ and $x_W = (m_W/m_{u_4})$,

Colliders	Linac-LHC				muon collider
	QCD Explorer		Energy Frontier		
Beams	ep	γp	ep	γp	$\mu\mu$
$u_4(\text{P})$, SM decays					[46]
$u_4(\text{P})$, Anom decays					
$d_4(\text{P})$, SM decays					[46]
d_4 (P), Anom decays					
$q_4(\text{AP})$					
$q_4(\text{S})$	[74, 76]				
$q_4(\text{S, A})$, SM decays					
q_4 (S, A), Anom decays	[62, 63, 72]				
$l_4(\text{P})$					[46]
$\nu_4(\text{P})$					[46]
$l_4\nu_4$ (AP)					
$l_4(\text{S, A})$	[57]		[57]		
ν_4 (S, A)	[61]		[61]		
Scalar Quarkonia					
Vector Quarkonia					[46], [47]
Hadrons					[47]

Table VII: The papers considered production of the fourth SM family fermions at existing and planned high eergy colliders (cont.)

$$\Gamma(u_4 \rightarrow Zq) = \frac{\alpha_e m_{u_4}^3}{16 \cos^2 \theta_W \sin^2 \theta_W} \left(\frac{\kappa_Z^q}{\Lambda} \right)^2 \varsigma_Z \sqrt{\varsigma_1} \quad (3)$$

where $\varsigma_Z = (2 - x_Z^4 - x_Z^2 - 4x_q^2 - x_q^2 x_Z^2 - 6x_q x_Z^2 + 2x_q^4)$, $\varsigma_1 = (1 + x_Z^4 + x_q^2 - 2x_Z^2 - 2x_q^2 - 2x_Z^2 x_q^2)$ and $x_Z = (m_Z/m_{u_4})$,

$$\Gamma(u_4 \rightarrow gq) = \frac{2\alpha_s m_{u_4}^3}{3} \left(\frac{\kappa_g^q}{\Lambda} \right)^2 \varsigma_2 \quad (4)$$

where $\varsigma_2 = (1 - 3x_q^2 + 3x_q^4 - x_q^6)$,

$$\Gamma(u_4 \rightarrow \gamma q) = \frac{\alpha_e m_{u_4}^3 Q_q^2}{2} \left(\frac{\kappa_\gamma^q}{\Lambda} \right)^2 \zeta_2. \quad (5)$$

The partial decay widths of d_4 for SM ($d_4 \rightarrow W^- q$ where $q = u, c, t$) and anomalous ($d_4 \rightarrow \gamma q, d_4 \rightarrow Zq, d_4 \rightarrow gq$ where $q = d, s, b$) modes are given below:

$$\Gamma(d_4 \rightarrow W^- q) = \frac{|V_{qd_4}|^2 \alpha_e m_{d_4}^3}{16 M_W^2 \sin^2 \theta_W} \chi_W \sqrt{\chi_0} \quad (6)$$

where $\chi_W = (1 + y_q^4 + y_q^2 y_W^2 - 2y_q^2 - 2y_W^4 + y_W^2)$, $\chi_0 = (1 + y_W^4 + y_q^4 - 2y_W^2 - 2y_q^2 - 2y_W^2 y_q^2)$, $y_q = (m_q/m_{d_4})$ and $y_W = (m_W/m_{d_4})$,

$$\Gamma(d_4 \rightarrow Zq) = \frac{\alpha_e m_{d_4}^3}{16 \cos^2 \theta_W \sin^2 \theta_W} \left(\frac{\kappa_Z^q}{\Lambda} \right)^2 \chi_Z \sqrt{\chi_1} \quad (7)$$

where $\chi_Z = (2 - y_Z^4 - y_Z^2 - 4y_q^2 - y_q^2 y_Z^2 - 6y_q y_Z^2 + 2y_q^4)$, $\chi_1 = (1 + y_Z^4 + y_q^2 - 2y_Z^2 - 2y_q^2 - 2y_Z^2 y_q^2)$ and $y_Z = (m_Z/m_{d_4})$,

$$\Gamma(d_4 \rightarrow gq) = \frac{2\alpha_s m_{d_4}^3}{3} \left(\frac{\kappa_g^q}{\Lambda} \right)^2 \chi_2 \quad (8)$$

where $\chi_2 = (1 - 3y_q^2 + 3y_q^4 - y_q^6)$,

$$\Gamma(d_4 \rightarrow \gamma q) = \frac{\alpha_e m_{d_4}^3 Q_q^2}{2} \left(\frac{\kappa_\gamma^q}{\Lambda} \right)^2 \chi_2. \quad (9)$$

One can wonder what is the criteria for the dominance of anomalous decay modes over SM ones. It is seen from Eq. (6)-(9) that the anomalous decay modes of the fourth SM family quarks are dominant, i.e. $\Gamma(d_4 \rightarrow gq) + \Gamma(d_4 \rightarrow Zq) + \Gamma(d_4 \rightarrow \gamma q) > \Gamma(d_4 \rightarrow W^- q)$, if the relation $(\kappa/\Lambda) \gtrsim 1.2(V_{ud_4}^2 + V_{cd_4}^2 + V_{td_4}^2)^{1/2} \text{ TeV}^{-1}$ is satisfied (hereafter $\kappa_Z^q = \kappa_g^q = \kappa_\gamma^q = \kappa$ is assumed). The experimental upper bounds for the fourth family quark CKM matrix elements are $|V_{u_4 d}| \leq 0.063$, $|V_{u_4 s}| \leq 0.46$, $|V_{u_4 b}| \leq 0.47$, $|V_{ud_4}| \leq 0.044$, $|V_{cd_4}| \leq 0.46$, $|V_{td_4}| \leq 0.47$ [64]. On the other hand, the predicted values of these matrix elements are expected to be rather small in the framework of flavor democracy hypothesis. For example, the mass matrix parametrization proposed in [17], which gives correct predictions for CKM and MNS mixing matrix elements through use of SM fermion mass values as input, predicts $|V_{u_4 d}| = 0.0005$, $|V_{u_4 s}| = 0.0011$, $|V_{u_4 b}| = 0.0014$, $|V_{ud_4}| = 0.0002$, $|V_{cd_4}| = 0.0012$, $|V_{td_4}| = 0.0014$. In

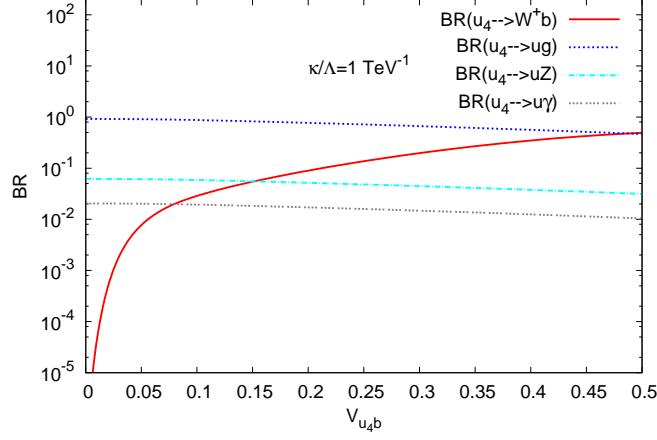


Figure 2: Branching ratio of u_4 versus V_{u_4b} graphic for $(\kappa/\Lambda) = 1\text{TeV}^{-1}$.

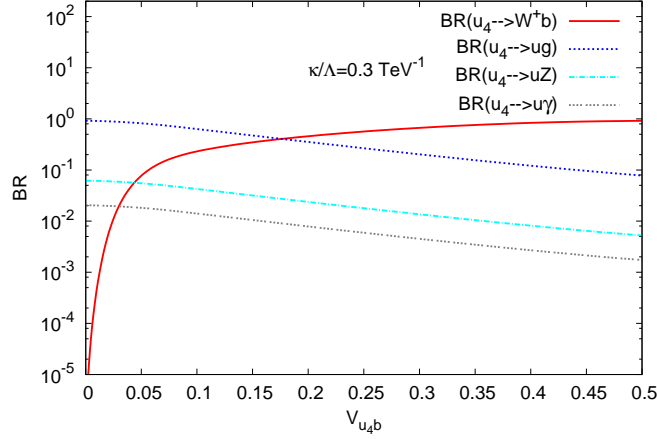


Figure 3: Branching ratio of u_4 versus V_{u_4b} graphic for $(\kappa/\Lambda) = 0.3\text{TeV}^{-1}$

this case, the anomalous decay modes are dominant, if $(\kappa/\Lambda) > 0.0022\text{ TeV}^{-1}$. The latter corresponds to upper limit 500 TeV for new physics scale Λ , assuming $\kappa = O(1)$.

In Figs 2-5, we plotted branching ratios of u_4 quark as a function of V_{u_4b} for different values of κ/Λ . Branching ratios of u_4 quarks as a function of κ/Λ for different values of V_{u_4b} are shown Figs. 6-8. It is seen that the assumption of the dominance of anomalous decay modes is quite realistic, especially for small CKM mixing parameters. Total decay widths of u_4 and d_4 quarks depending on their masses were plotted in Fig 9 and 10, respectively.

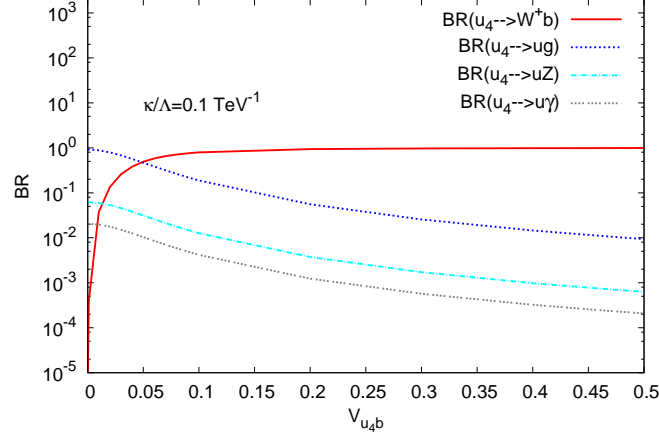


Figure 4: Branching ratio of u_4 versus V_{u_4b} graphic for $(\kappa/\Lambda) = 0.1 \text{ TeV}^{-1}$

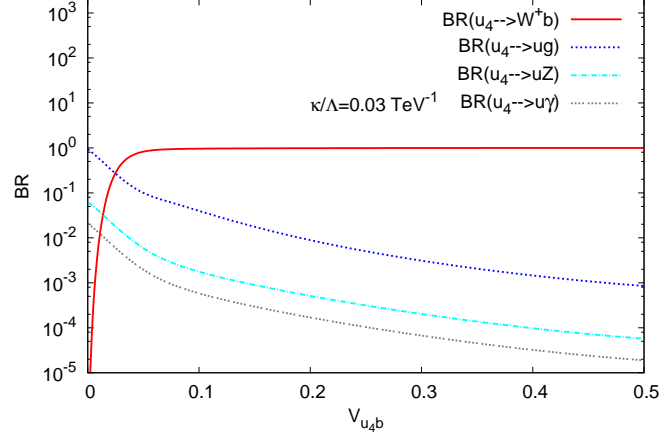


Figure 5: Branching ratio of u_4 versus V_{u_4b} graphic for $(\kappa/\Lambda) = 0.03 \text{ TeV}^{-1}$

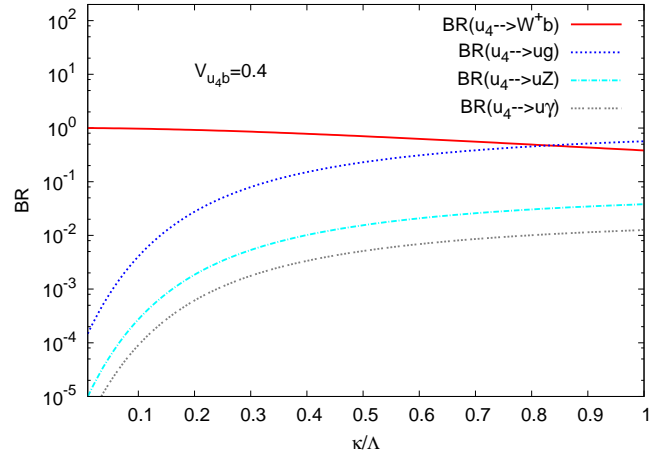


Figure 6: Branching ratio of u_4 versus (κ/Λ) graphic for $V_{u_4b} = 0.4$

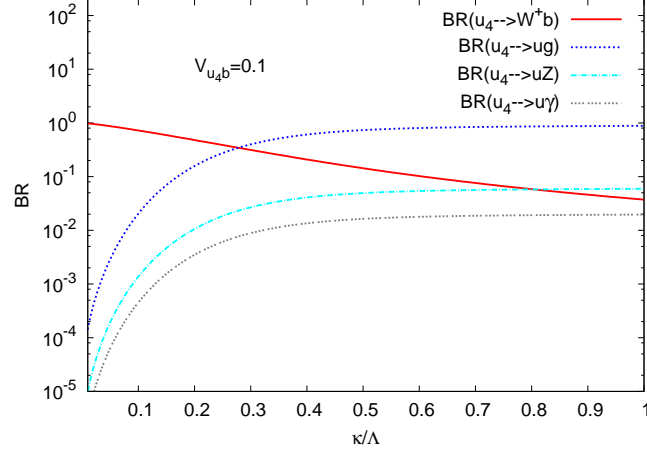


Figure 7: Branching ratio of u_4 versus (κ/Λ) graphic for $V_{u_4b} = 0.1$

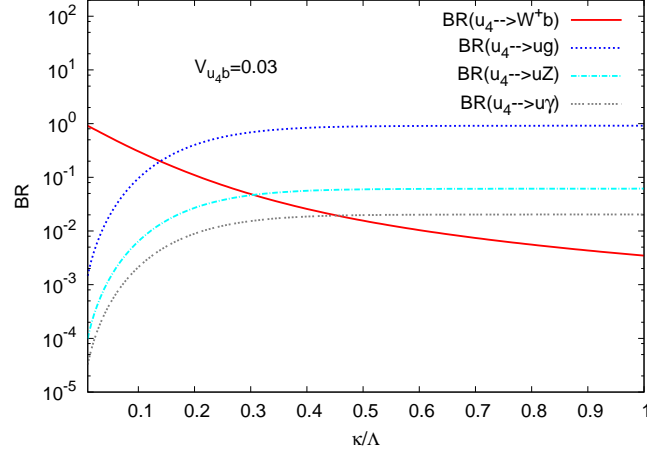


Figure 8: Branching ratio of u_4 versus (κ/Λ) graphic for $V_{u_4b} = 0.03$

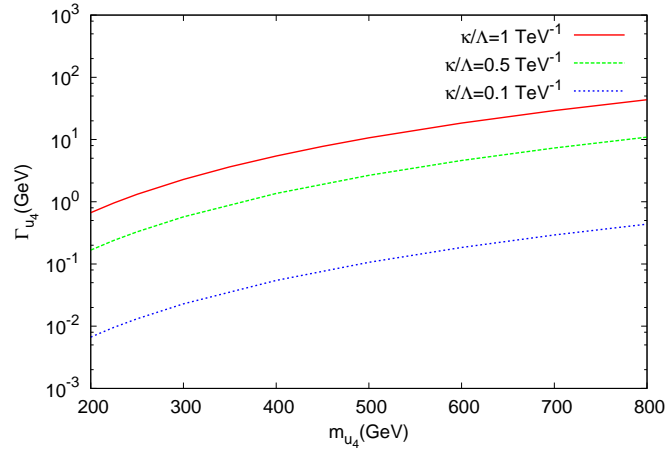


Figure 9: Anomalous decay width of u_4 .

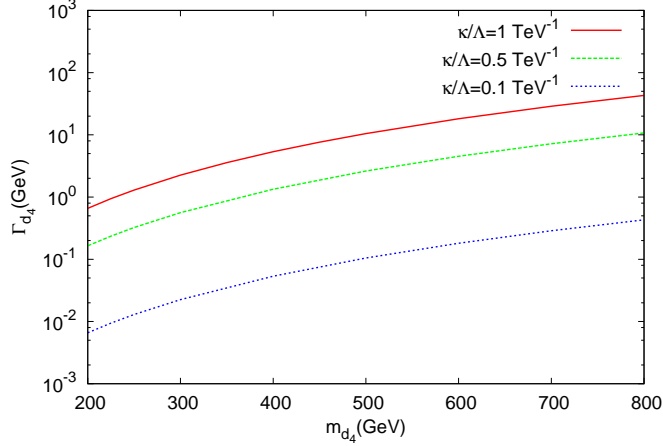


Figure 10: Anomalous decay width of d_4 .

IV. PAIR d_4 PRODUCTION AT TEVATRON AND LHC WITH SUBSEQUENT ANOMALOUS DECAYS

In this section, we study pair production of d_4 quarks at the Tevatron and LHC. For the numerical calculations we implement anomalous interaction lagrangian of the fourth family quarks into CalcHEP package program [83] and we used CTEQ6L [84] parton distribution functions with factorization scale $Q^2 = m_{d_4}^2$. The pair production cross sections of $d_4\bar{d}_4$ at the Tevatron and LHC are plotted in Fig. 11. It is seen that i.e. for $m_{d_4} = 300$ GeV pair production cross section at LHC with $\sqrt{s} = 7$ TeV is 20 times larger than at Tevatron. This ratio can be used to compare Tevatron and LHC capacities. Namely, for $m_{d_4} = 300$ GeV LHC need twenty times less luminosity than the Tevatron.

Pair production of fourth SM family quarks at hadron colliders have been analysed in a number of papers (see corresponding rows in the Table VI) assuming SM decays. For this reason below we consider the process $p\bar{p}(p) \rightarrow d_4\bar{d}_4X \rightarrow g d\gamma\bar{d}X$ in order to compare the Tevatron and LHC search potential in the case where anomalous decays are dominant. This process will be seen in dedector as $\gamma + 3j$ events, for background calculations we use MADGRAPH package [85].

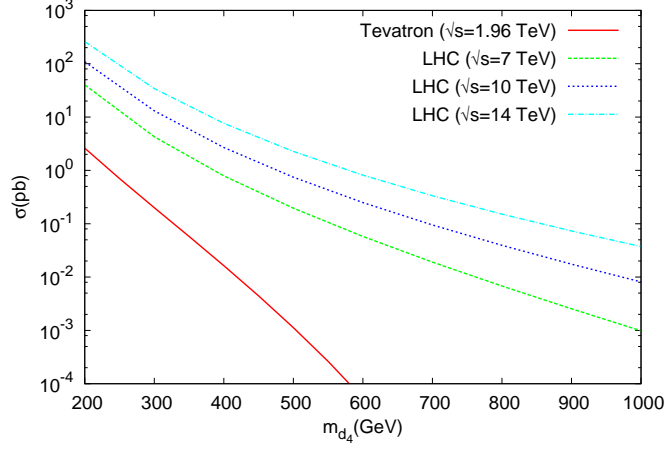


Figure 11: The pair production cross section of $d_4\bar{d}_4$ at the Tevatron and LHC

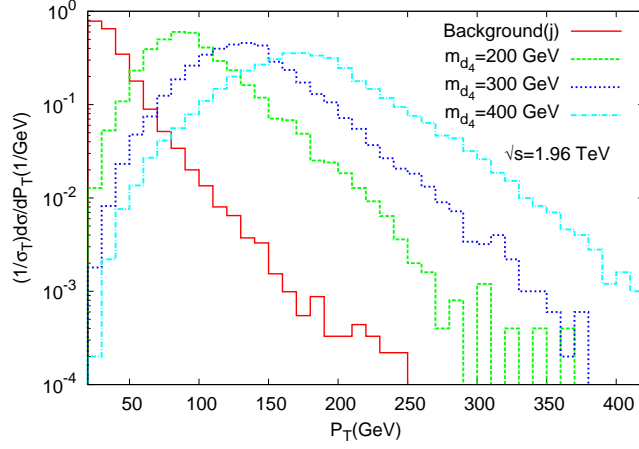


Figure 12: Normalised p_T distributions of partons for signal and background for pair d_4 production at the Tevatron.

A. Signal and Background Analysis at the Tevatron

Normalized transverse momentum (p_T) and pseudo-rapidity (η) distributions of final state partons (quarks, photon and gluon) for signal and background processes are shown in Fig. 12 and Fig. 13, respectively. It is seen that $p_T > 50$ GeV cut essentially reduces background, whereas signal is almost unaffected. In addition to $p_T > 50$ GeV, we have used CDF cut value $|\eta| < 2$ for pseudo-rapidity, as well as invariant mass within ± 20 GeV around d_4 mass. In table VIII we present the values of the signal and background cross-sections for different cuts.

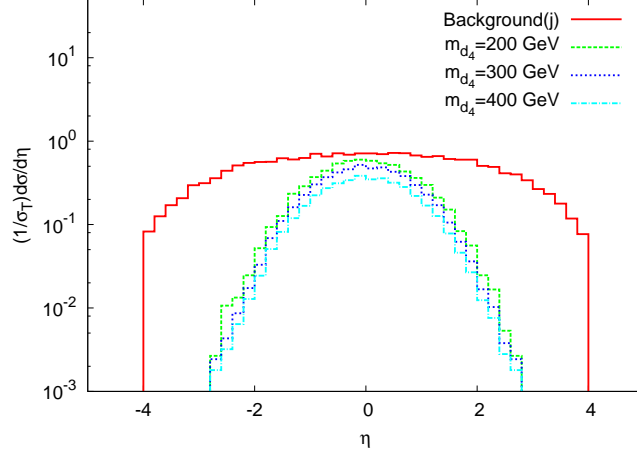


Figure 13: Normalized η distributions of partons of signal and background for pair d_4 production at the Tevatron.

M_{d_4}	200 GeV		300 GeV		400 GeV	
cuts	σ_S , fb	σ_B , fb	σ_S , fb	σ_B , fb	σ_S , fb	σ_B , fb
$p_T > 20\text{GeV}$	39.2	5.4×10^5	2.92	5.4×10^5	0.23	5.4×10^5
$p_T > 50\text{GeV}$	24.5	2.7×10^3	2.40	2.7×10^3	0.21	2.7×10^3
all cuts	21.8	3.63	2.27	0.091	0.20	0.006

Table VIII: Signal and background cross sections values for various cuts at Tevatron [14]. All cuts include $p_T > 50$ GeV, $|\eta| < 2$, $|M_{inv}(\gamma j) - M_{d_4}| < 20$ GeV, $|M_{inv}(jj) - M_{d_4}| < 20$ GeV.

Statistical significance has been calculated by using following formula [86]:

$$S = \sqrt{2[(s+b)\ln(1 + \frac{s}{b}) - s]} \quad (10)$$

where s and b represents the numbers of signal and background events, respectively.

In Fig. 14 we plot the necessary luminosity for 2σ exclusion, 3σ observation and 5σ discovery limits depending on d_4 mass. Reachable masses for d_4 quark at different values of the Tevatron integrated luminosity are presented in Table IX.

B. Signal and Background Analysis at the LHC

Normalized transverse momentum (p_T) and pseudo-rapidity (η) distributions of final state partons (quarks, photon and gluon) for signal and background processes are shown in Fig.

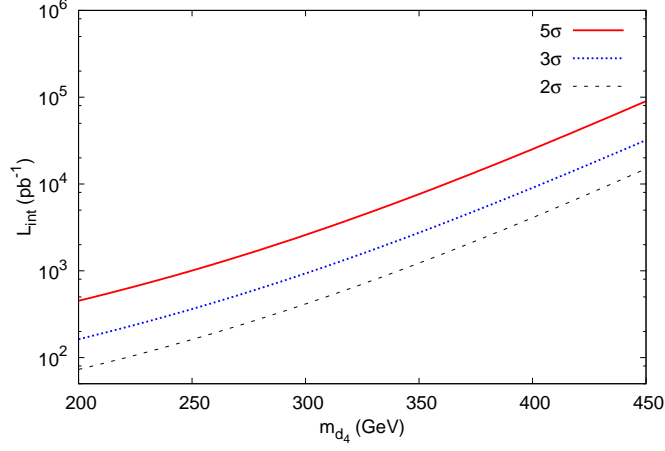


Figure 14: The necessary integrated luminosity for exclusion, observation and discovery of d_4 quark at the Tevatron [14].

L_{int}, fb^{-1}	5	10	20
2 σ exclusion	390 GeV	430 GeV	460 GeV
3 σ observation	370 GeV	410 GeV	440 GeV
5 σ discovery	340 GeV	360 GeV	390 GeV

Table IX: Reachable m_{d_4} mass values for discovery, observation, and exclusion at the Tevatron [14].

15 and Fig. 16, respectively. It is seen that $p_T > 50$ GeV cut essentially reduces background, whereas signal is almost unaffected. In addition to $p_T > 50$ GeV, we have used ATLAS cut value $|\eta| < 2.5$ for pseudo-rapidity, as well as invariant mass within ± 20 GeV around d_4 mass. In Table X we present the values of the signal and background cross-sections for different cuts.

M_{d_4}	200 GeV		300 GeV		400 GeV		500 GeV	
cuts	σ_S, fb	σ_B, fb	σ_S, fb	σ_B, fb	σ_S, fb	σ_B, fb	σ_S, fb	σ_B, fb
$p_T > 20$ GeV	3.77×10^3	7.44×10^6	394	7.44×10^6	71.1	7.44×10^6	19.2	7.44×10^6
$p_T > 50$ GeV	2.14×10^3	1.12×10^5	319	1.12×10^5	63.7	1.12×10^5	17.9	1.12×10^5
all cuts	315	13.62	46.94	1.03	9.3	0.59	2.4	0.037

Table X: Signal and background cross sections values for various cuts at the LHC. All cuts include $p_T > 50$ GeV, $|\eta| < 2.5$, $|M_{inv}(\gamma j) - M_{d_4}| < 20$ GeV, $|M_{inv}(jj) - M_{d_4}| < 20$ GeV.

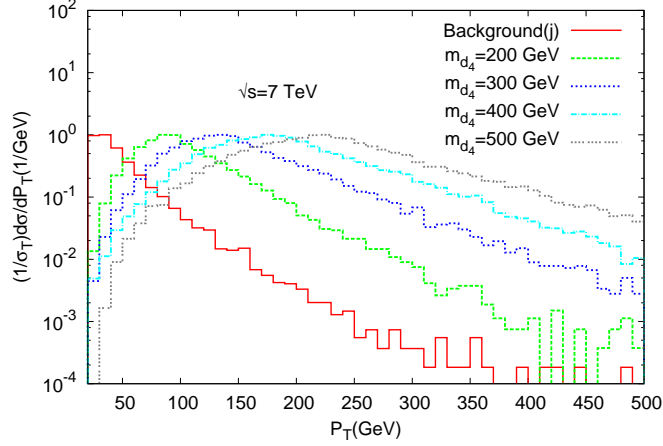


Figure 15: Normalised p_T distributions of partons for the signal and background for pair d_4 production at the LHC.

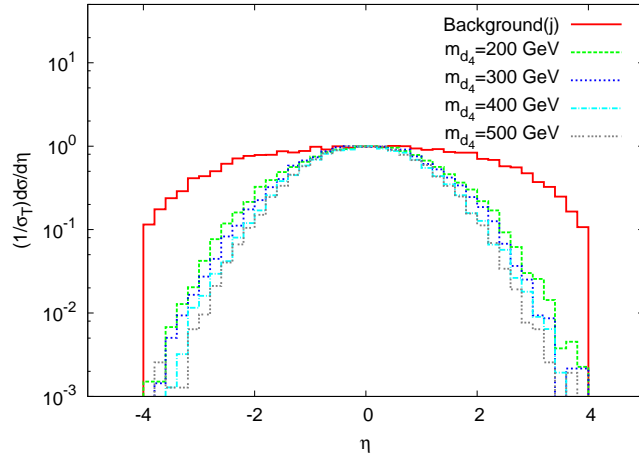


Figure 16: Normalised η distributions of partons for the signal and background for pair d_4 production at the LHC.

In Fig. 17 we plot the necessary luminosity for 2σ exclusion, 3σ observation and 5σ discovery limits depending on d_4 mass. Reachable masses for d_4 quark at different values of the Tevatron integrated luminosity are presented in Table XI.

Comparing Tables IX and XI, one can conclude that LHC with $\sqrt{s} = 7$ TeV and integrated luminosity $L_{int} = 300 \text{ pb}^{-1}$ surpasses the Tevatron with $L_{int} = 10 \text{ fb}^{-1}$.

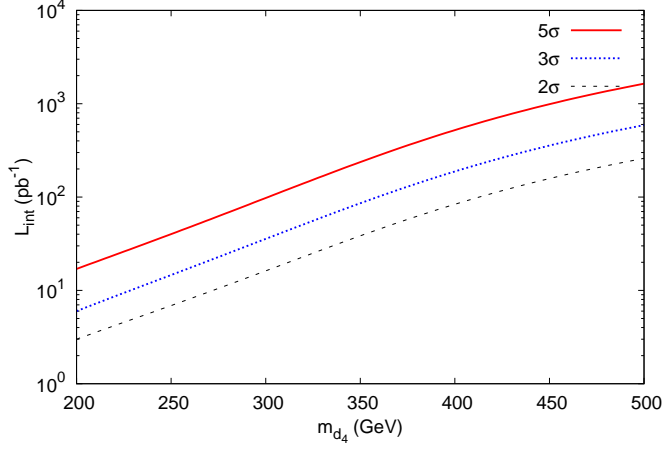


Figure 17: The necessary integrated luminosity for exclusion, observation and discovery of d_4 quark at the LHC.

L_{int}, pb^{-1}	100	300	1000
2 σ exclusion	420 GeV	510 GeV	640 GeV
3 σ observation	370 GeV	430 GeV	550 GeV
5 σ discovery	310 GeV	360 GeV	460 GeV

Table XI: Reachable m_{d_4} mass values for discovery, observation, and exclusion at the LHC.

V. ANOMALOUS RESONANT u_4 PRODUCTION AT TEVATRON AND LHC WITH SUBSEQUENT ANOMALOUS DECAY

Total cross sections for the anomalous resonant production of u_4 quark at the Tevatron and LHC are shown in Fig. 18. It is seen that for $m_{d_4} = 300$ GeV the cross section at the LHC with $\sqrt{s} = 7$ TeV is 40 times larger than the cross section at the Tevatron.

A. Signal and Background Analysis at the Tevatron

The $p\bar{p} \rightarrow u_4 X \rightarrow \gamma u X$ process is considered as a signature of anomalous resonant production of fourth SM family up type quark. The SM background for this process is $p\bar{p} \rightarrow \gamma j X$, where $j = u, \bar{u}, d, \bar{d}, c, \bar{c}, s, \bar{s}, b, \bar{b}, g$. In order to determine appropriate kinematical cuts, p_T and η distributions for signal and background processes are given in Fig. 19 and Fig. 20, respectively.

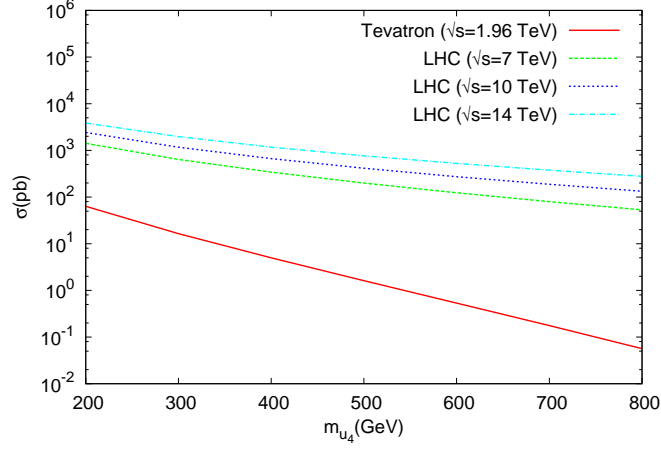


Figure 18: The anomalous resonant production cross sections of u_4 at Tevatron and LHC.

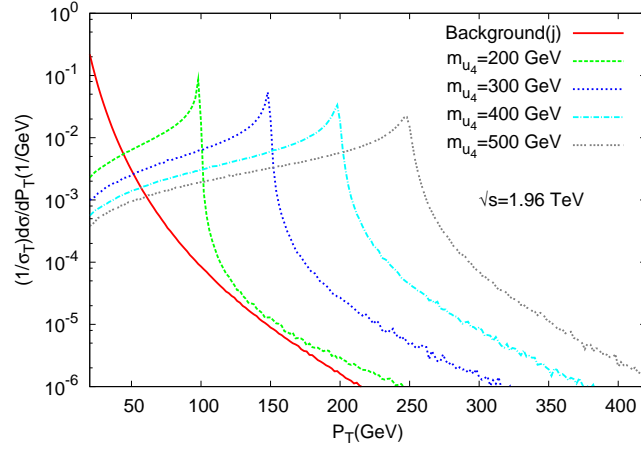


Figure 19: Normalised p_T distributions of partons for the signal and background for anomalous resonant u_4 production at the Tevatron.

In order to extract the u_4 signal and to suppress the background, the following cuts are applied: $p_T > 75$ GeV and $|\eta| < 2$ for all final state partons and photon, as well as invariant mass within ± 20 GeV around the u_4 mass. For the signal calculations $\kappa/\Lambda = 0.1 \text{TeV}^{-1}$ have been used.

In Fig. 21 we plot the necessary luminosity for 2σ exclusion, 3σ observation and 5σ discovery limits depending on u_4 mass. Reachable masses for u_4 quark at different values of the Tevatron integrated luminosity are presented in Table XII.

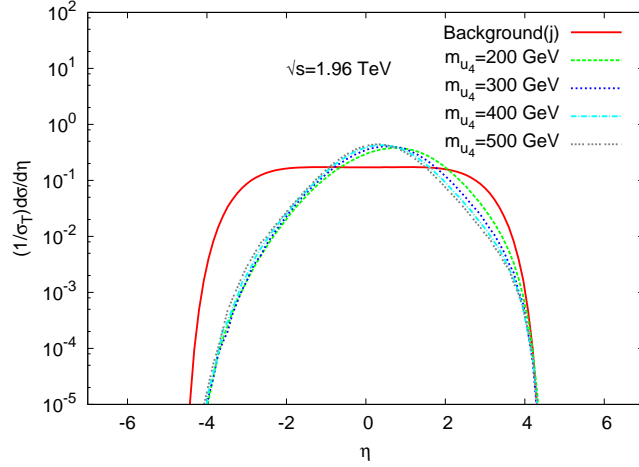


Figure 20: Normalised η distributions of partons for the signal and background for anomalous resonant u_4 production at the Tevatron.

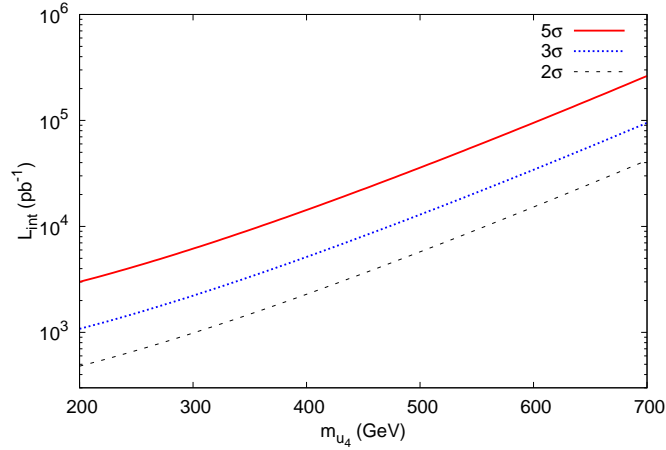


Figure 21: The necessary integrated luminosity for exclusion, observation and discovery of u_4 quark at the Tevatron

L_{int}, fb^{-1}	5	10	20
2σ exclusion	480 GeV	560 GeV	630 GeV
3σ observation	400 GeV	470 GeV	540 GeV
5σ discovery	270 GeV	360 GeV	440 GeV

Table XII: Reachable m_{u_4} mass values for discovery, observation and exclusion at the Tevatron

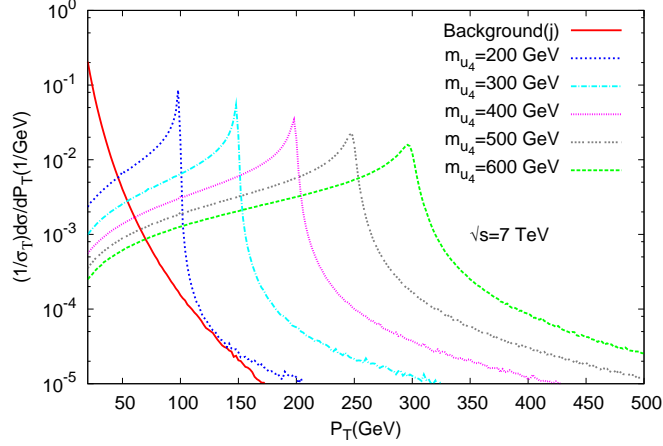


Figure 22: Normalised p_T distributions of partons for the signal and background for anomalous resonant u_4 production at the LHC.

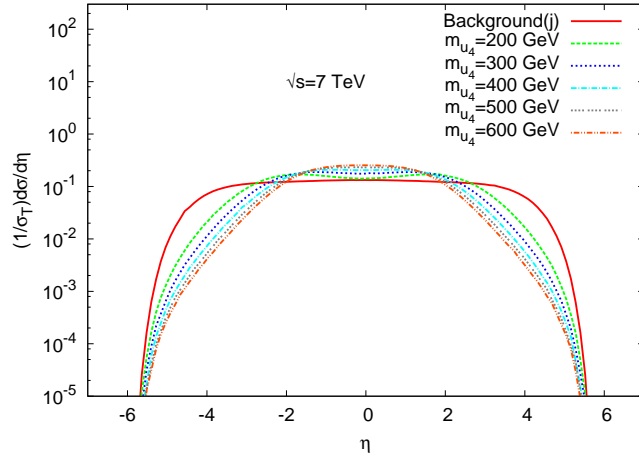


Figure 23: Normalised η distributions of partons for the signal and background for anomalous resonant u_4 production at the LHC.

B. Signal and Background Analysis at the LHC

In order to determine appropriate kinematical cuts, p_T and η distributions for signal and background processes are given in Fig. 22 and Fig. 23, respectively.

In order to extract the u_4 signal and to suppress the background, the following cuts are applied: $p_T > 75$ GeV and $|\eta| < 2.5$ for all final state partons and photon, as well as invariant mass within ± 20 GeV around the u_4 mass. For the signal calculations $\kappa/\Lambda = 0.1 \text{ TeV}^{-1}$ have been used.

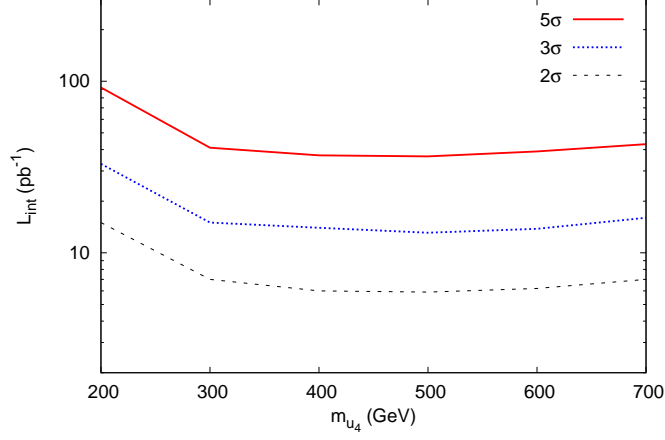


Figure 24: The necessary integrated luminosity for exclusion, observation and discovery of u_4 quark at the LHC

In Fig. 24 we plot the necessary luminosity for 2σ exclusion, 3σ observation and 5σ discovery limits depending on u_4 mass.

Comparing figures 21 and 24, it is obvious that LHC with $\sqrt{s} = 7$ TeV and integrated luminosity $L_{int} = 100 \text{ pb}^{-1}$ surpasses the Tevatron with $L_{int} = 10 \text{ fb}^{-1}$.

VI. CONCLUSION

It is seen that there is a tough competition between Tevatron and LHC in a search for Higgs boson and fourth family quarks. We have shown that in case the anomalous decay modes are dominant:

- a) for pair production, LHC with $\sqrt{s} = 7$ TeV and $L_{int} = 300 \text{ pb}^{-1}$ surpasses Tevatron with $L_{int} = 10 \text{ fb}^{-1}$,
- b) for anomalous resonant production, LHC with $L_{int} = 100 \text{ pb}^{-1}$ cover whole mass range if $\kappa/\Lambda = 0.1 \text{ TeV}^{-1}$.

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